A Comprehensive Analysis on Detection Performances and Robustness of LPI Signals Filtering Strategies

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***Abstract* — This paper focuses on the detection performances achievable in the presence of Low Probability of Intercept (LPI) radar signals. It is well known that the radar community is widely investigating LPI waveforms to reduce the Range Advance Factor (RAF) obtainable with Electronic Support Measure (ESM) systems. Several filtering strategies for LPI signals processing are already available in open literature, but a formal analysis on different detection strategies and a comparison on the detection probability has not yet carried out. In this paper we propose several detectors, using different signal filtering algorithms and different detection strategies. Moreover a comprehensive analysis for all the proposed receivers is carried out for different LPI waveform, also in comparison with the classical Fast Fourier Transform (FFT) filtering, widely adopted by current ESM systems. Finally, an analysis in presence of non-LPI interfering signal has been carried out to asses the robustness of the different algorithms.**

***Keywords* — ESM, LPI, Detection Performances.**

I. Introduction

The use of ESM sensors [1][2][3] offers great advantages with respect to the use of traditional radar systems

- the lower cost of passive ESM sensors with respect to classical radar, due to the receiving only architecture;
- the un-detectability of the system, thanks to the passive based detection strategy;
- the all time and all weather capabilities, due to the intrinsic higher robustness to the sea-state (sea clutter) and rain (volumetric clutter), with respect to classical radar systems;
- the possibility to operate in very dense environments using the higher number of discrimination degree of freedom with respect to traditional radar, like emitter waveforms traditional parameters: frequency, Pulse Repetition Interval (PRI), Pulse Width (PW) etc.;
- the ability to resolve targets very close one each other exploiting digital signal and data processing techniques, such as pulse train deinterleaving, thus solving the problem of track-plot association which can be very complex for radar in a dense scenario;
- the possibility to not only detect, but also identify targets by means of a-priori information, stored in the emitter library;
- the exploitation of Specific Emitter Identification (SEI) techniques to identify in unique way the emitters pertaining to a specific platform;
- the higher detection range obtainable exploiting the one way signal attenuation.

In particular this last point is well known both to the radar as well as to the Electronic Warfare (EW) communities, and usually gives to ESM systems a RAF higher than 1 allowing the passive system to detect threats before than active radar systems [4][5]. In such way the platform equipped with the ESM system can use Electronic Attack (EA) or other defence suppression actions, thereby reducing its vulnerability to attack. Conversely, if the LPI radar can detect the platform before it is alerted by its ESM system, then the platform becomes vulnerable to offensive actions.

Traditional techniques to enhance the LPI capability of radar waveforms usually consist in [6][7][8][9]

- very low peak power;
- radiating energy spread over a wide frequency bandwidth (BW) and long time interval;
- coherent processing with high number of integrated pulses;
- low sidelobe transmit antenna;
- reduced receiver noise temperature and losses.

In particular, one of the most effective methods for reducing the ESM RAF is the adoption of ultra wide bandwidth pulses: in this way the radar transmitted signal is mismatched to the waveforms the ESM system is expected to receive.

There are many wideband modulation techniques available that provides LPI features [6][10][11][12][13][14] such as linear (i.e. chirp) and non linear frequency modulations, discrete phase coding modulations (e.g. Frank code, Px codes, generalized Barker, etc.), frequency hopping modulations (e.g. Costas), pseudo-noise waveform etc.

A classical filtering strategy widely adopted in current digitally based ESM systems, rely on the Fourier domain, by means of FFT processing [15]. This approach is considered robust and exhibit well assessed performances under the assumption of non modulated pulses or in the case of modulated pulses with BW spreading in the order of the FFT bin size. Unfortunately, for LPI radar waveforms, the single

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pulse exhibits a BW wider with respect to the FFT frequency bin. In those cases, more sophisticated filtering procedures are needed.

Several filtering strategies for processing LPI signals are already available in open literature: for example in [16][17], filtering methods based on the Cyclostationary signal properties are proposed such as FFT Accumulation Method (FAM) and the Strip Spectral Correlation Analysis (SSCA). Moreover in [11][12][14][18][19] other approaches are proposed for example based on time-frequency analysis such as the Wigner-Ville Distribution (WVD) and the Quadrature Mirror Filtering (QMF).

In open literature those signal filtering approaches are presented and analyzed in terms of behavior with respect to different signal inputs, and all the bi-dimensional output are shown and analyzed, and some classification hints are given.

Nevertheless, detectors based on those filtering strategies have not yet been formally analyzed. In this paper we propose different decision strategies for each filtering procedure, and evaluate the performances in terms of Probability of Detection (Pd) once the Probability of False Alarm (Pfa) has been fixed, according to the Neyman-Pearson criteria.

The analyses have been carried out with different LPI signals and also in comparison with classical detection strategies based on FFT filtering, also in the presence of interfering Continuous Waveform (CW) signal.

II. Filtering Strategies

In this section the different filtering procedures available in open literature [11][16][17][18] are shortly recalled.

In particular the first filtering procedure we will apply is the classical FFT, applied both over a single frame as well as over N consecutive and partially overlapped frames.

As to the other filtering procedure, in this paper will be analyzed

- FAM filtering procedure (see Fig. 1)
- SSCA filtering procedure (see Fig. 2)
- QMF filtering procedure (see Fig. 3)

For lack of space only the main block scheme of the analyzed filtering procedures are depicted. Nevertheless, those filtering procedures are well described in open literature, and further details are available in references from [11] to [19].

III. Detectors Design

In this section we proposed two different detection strategies than can be applied to all the already recalled filtering procedures i.e. we obtain several receiver strategies based on FFT, FAM, SSCA, and QMF.

The complete receiving chain is shown in Fig. 4. The Digital Signal Processing is divided into the Filtering Strategy and the Detection Strategy. The Filtering Strategy will be one the previous mentioned algorithmic procedure. As to the Detection Strategy it has to be noted that all the filtering strategies gives as output vectors or matrices: the single FFT gives as output a vector, all the other filtering procedures gives as output bi-dimensional vector, i.e. matrices.

A first decision strategy is based on the selection of the maximum output of the filtering strategy. It has to be noted that this procedure allows the detection of a single signal for each statistical test. In the following we will denote this detector as Max Detector (MD).

A possible improvement of this decision strategy is a Non-Coherent integration of the Max Detector (NIMD): given a pre-defined number of contribution to be integrated (denoted as Nmax) the detection is performed on the sum of the Nmax greater contribution.

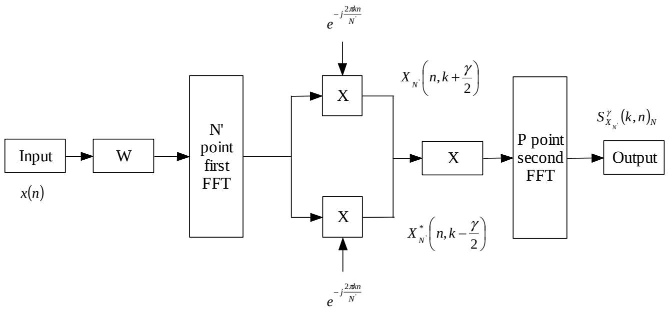

Fig. 1. Block diagram of the FAM filtering procedure.

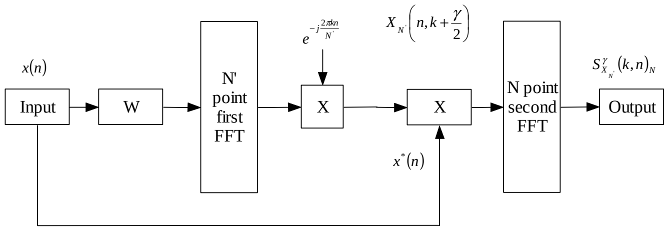

Fig. 2. Block diagram of the SSCA filtering procedure.

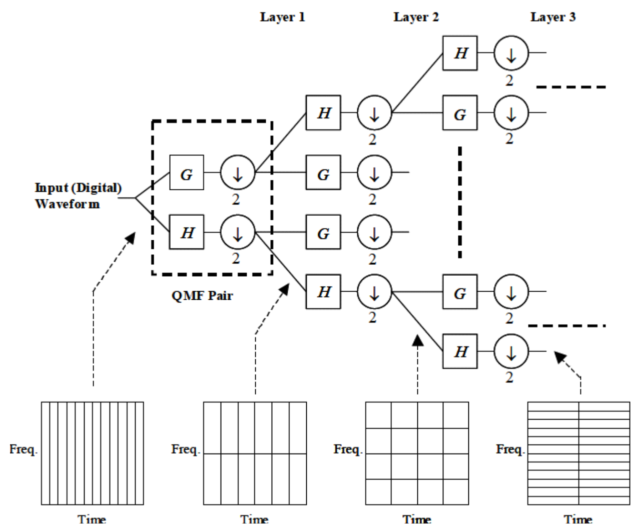

Fig. 3. Block diagram of the QMF filtering procedure.

This strategy take into account the feature of the LPI signal that usually are spread over time and frequency: performing the detection over the several contribution the detection performance can be improved. Nevertheless, the choice of Nmax highly depends both on

- the filtering strategy;
- the receiver parameters (number of processed samples, filtering settings etc.);
- the LPI input waveform and parameters.

A properly choice for the Nmax parameter has been performed for each filtering strategies by means of extensive simulations.

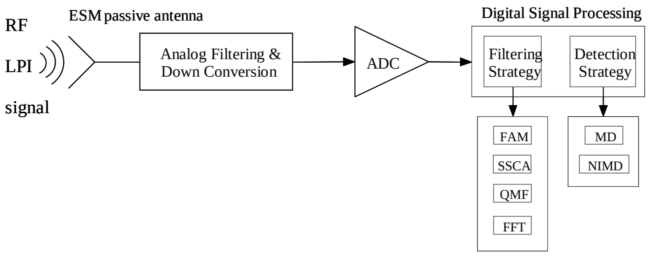

Fig. 4. Block scheme of the simulated receiver chain with the different filtering strategies and the proposed detectors.

By doing so, the following reception strategies have been analyzed

- FFT on a single time frame with MD (denoted as FFT-MD-frame);
- FFT with MD on a single frame and with binary integration M over N with M=2 and N=3 (denoted as FFT-MD-binary);
- FFT with MD over the total signal length (FFT-MD);
- FAM with MD (FAM-MD);
- SSCA with MD (SSCA-MD);
- QMF layer 4 with MD (QMF4-MD)
- FAM with NIMD (FAM-NIMD);
- SSCA with NIMD (SSCA-NIMD);
- QMF layer 4 with NMID (QMF4-NIMD).

IV. LPI ANALYZED SIGNALS

Three different types of signals have been used to analyze the performance of the receiver presented in the previous section. The fundamental signals parameters and the representation of the signal in the time-frequency domain are provided below

- Chirp signal with carrier frequency f_c=200 MHz, slope=200 MHz/µs and duration T=0.8 µs (Fig. 5);
- Frank coded signal with carrier frequency f_c=200 MHz, cycle per phase cpp=1 and frequency steps M=4 (Fig. 6);
- Costas coded signal with frequencies f=400,700,100,600, 500,200,300 MHz and cycle per frequency cpf=10 (Fig. 7).

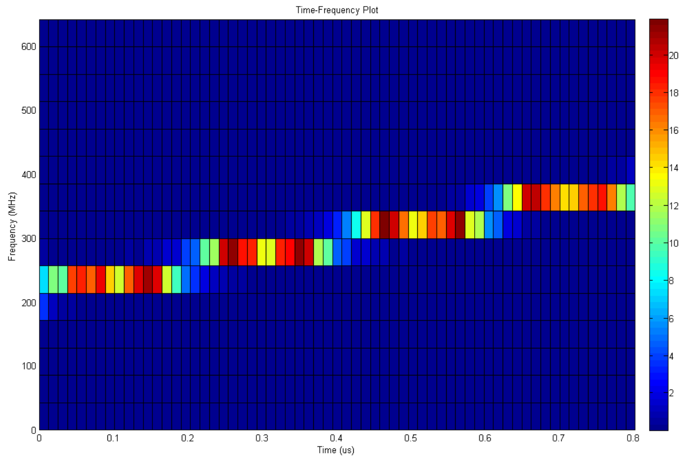

Fig. 5. Time-Frequency plot of the chirp signal (output of the QMF layer 4 time-frequency analysis).

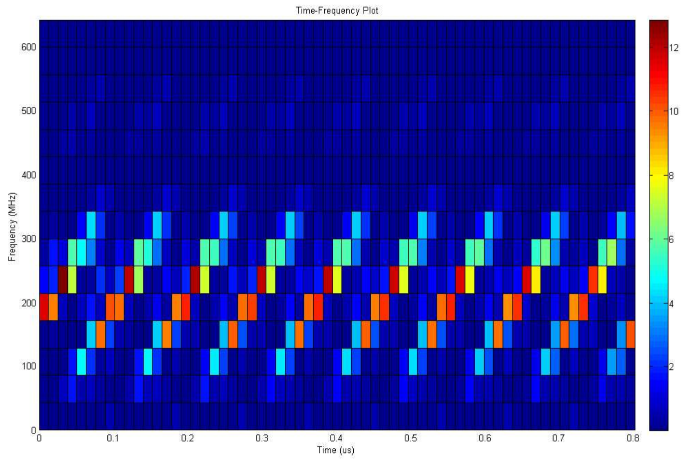

Fig. 6. Time-Frequency plot of the Frank coded signal (output of the QMF layer 4 time-frequency analysis).

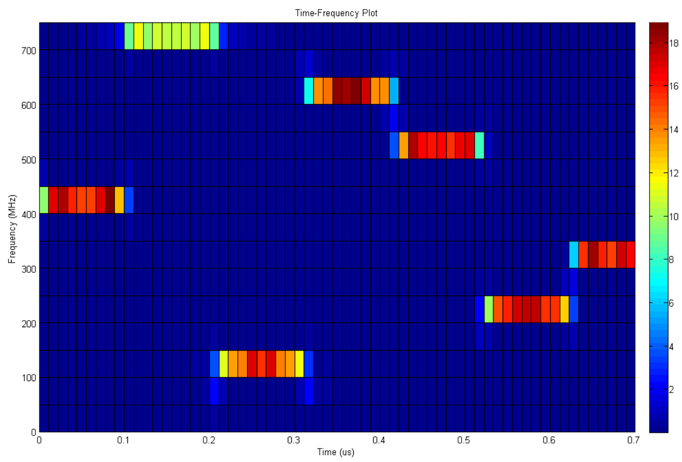

Fig. 7. Time-Frequency plot of the Costas coded signal (output of the QMF layer 4 time-frequency analysis).

V. Receiver Parameters and Performance Analysis

The receiver sampling frequency is equal to 1280 Mhz and the total analyzed signal is composed by 1024 samples (i.e. the total analyzed signal length is 0.8μs). For the strategies that require frame segmentation of the input signal, the frame duration has been set to 64 samples. A Blackman-Harris windowing and 50% overlap has been applied, having by doing so 31 frames.

The threshold is set through Montecarlo simulation to achieve a Pfa=10^{-2}, i.e. using 10000 trials (100/Pfa). Also the Pd curves have been determinate trough Montecarlo simulations using 1000 trials. The Signal to Noise Ratio (SNR) is defined over a single sample, i.e. SNR = $A^2/2\sigma^2$, with A useful signal amplitude and σ noise standard deviation.

In Fig. 8 are reported the Pd performances for a chirp input signal: the FAM-MD, SSCA-MD and QMF4-MD exhibit better performances with respect to all the FFT based strategies, with a gain in the order of 5 dB for Pd>0.9. Moreover, using the NIMD detection strategy, the overall gain increase arriving up to 9 dB. Anyway it has to be underlined that the total number of samples used by the FFT-MD-frame (64 samples) and FFT-MD-binary (128 samples) is lower with respect to all the other strategies (1024 samples).

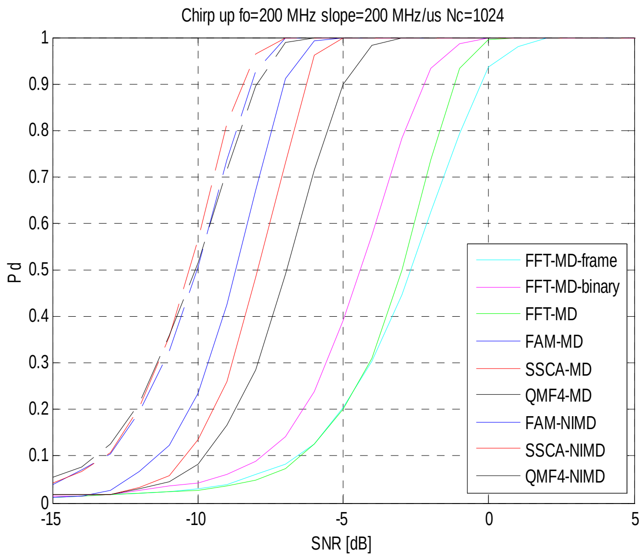

Fig. 8. Performances for the chirp signal.

Fig. 9 refers to the Frank coded signal. The FFT-MD is very close to the FAM-MD and outperform QMF4-MD and SSCA-MD. In fact Fig. 6 shows that the main signal contribution frequency is centered at the carrier frequency. The use of the NIMD decision strategy allow a gain of 2 dB with respect to the FFT-MD and 9 dB with respect to the FFT over a single frame.

Finally, in Fig. 10 is shown the gain for a Costas coded signal: all The FFT based detectors are outperformed and the gain for the NIMD based decision strategies ranges between 4 and 8 dB.

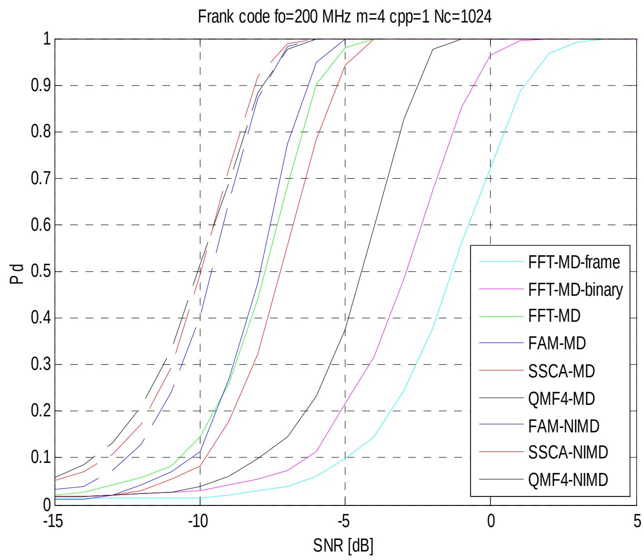

Fig. 9. Performances for the Frank coded signal.

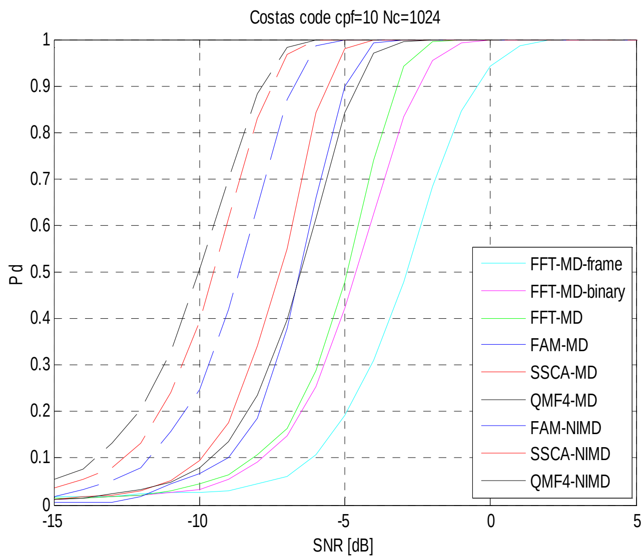

Fig. 10. Performances for the Costas coded signal.

VI. Analysis in Presence of CW Interfering Signal

This section shows the result of the previously analyzed algorithms in the presence of a CW interfering signal.

More precisely, the CW interfering signal have been simulated with a fixed frequency f_{cw}=300 MHz and with a power given by the Interference to Noise Ratio (INR) defined as INR = $B^2/2\sigma^2$, with B interfering signal amplitude.

The result for the FAM-MD algorithm and a chirp as useful signal is shown in Fig. 11 also with respect to the plain situation, i.e. the situation with no interfering signal (INR=-∞ dB). Fig. 11 shows that for INR=-20dB, the performances are almost equal to the plain situation; on the contrary, as INR increase, the curves change behavior, obtaining higher Pd values: this is due to the fact that the algorithm detects the CW signal instead of the LPI signal. For example for INR=-10 dB the FAM-MD algorithm exhibit always a Pd equal to 1: the CW signal is always above the threshold and, by doing so, the LPI signal is masked.

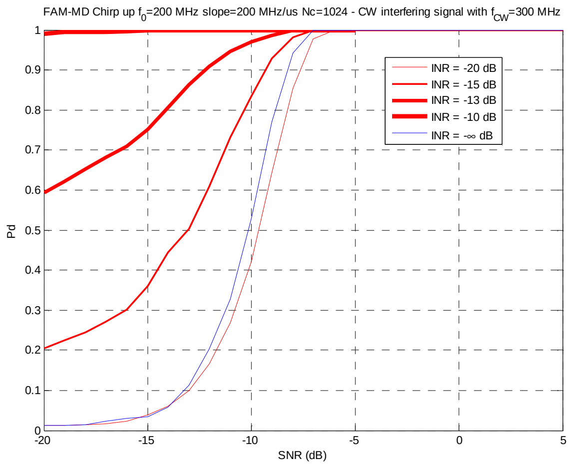

Fig. 11. Performances of the FAM-MD for the chirp signal, also in presence of interfering CW signal.

A very similar situation arise also for the FAM-NIMD algorithm: in Fig. 12 the performances are reported for several values of INR showing that even very low values of INR, in the order of -13dB, are sufficient to change the algorithm performances. A very similar behavior arises for the SSCA based detectors, not reported here for lack of space.

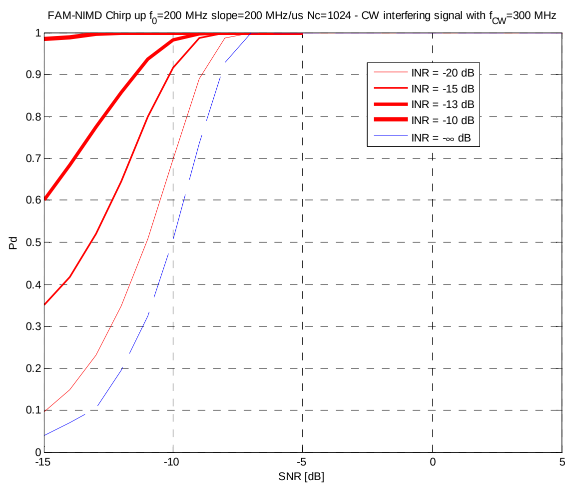

Fig. 12. Performances of the FAM-NIMD for the chirp signal, also in presence of interfering CW signal.

Finally, in Fig. 13 and Fig. 14 are reported the results for the QMF4 based detectors: also this algorithms exhibit the same behavior even if the values where the Pd saturation occur are higher with respect to the FAM based algorithms.
Nevertheless, all the analyzed situations clearly show that this detectors are not sufficiently robust in the presence of a CW signal, and interference mitigation strategies are required to deal with dense electromagnetic environments.

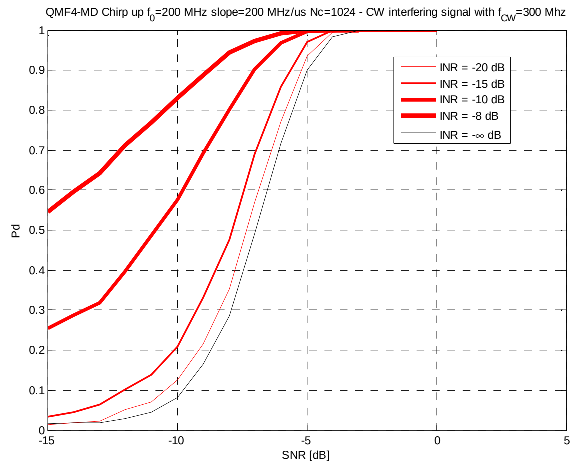

Fig. 13. Performances of the QMF4-MD for the chirp signal, also in presence of interfering CW signal.

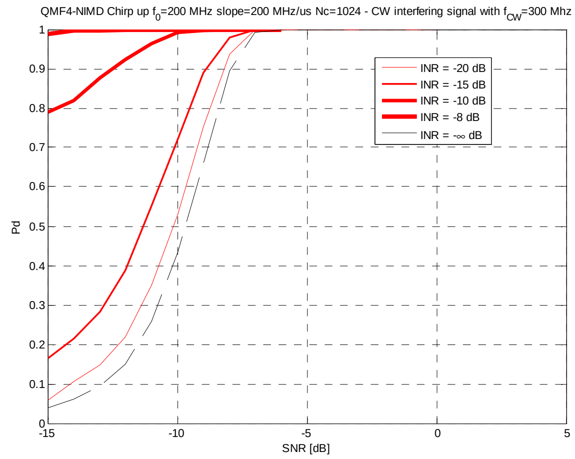

Fig. 14. Performances of the QMF4-NIMD for the chirp signal, also in presence of interfering CW signal.

VII. CONCLUSIONS

In this paper several filtering strategies for LPI signals processing have been analyzed and have been used to design LPI waveform detectors. A performance analysis in terms of Pd have been carried out for several detectors, using different detection strategies and different signal filtering algorithms, also in comparison with the classical FFT.

The results have shown performance gain that can arrive up to 9 dB with respect to a classical FFT processing over a single data frame, and up to 8 dB for the case of the FFT performed over the entire input signal.

Finally, analyses in presence of interfering signals have shown that all the algorithms suffer the presence of CW signals, and an inference mitigation strategy is required to operate in dense scenarios.

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